

DESIGN AND OPERATIONAL ASPECTS OF FLIGHT-DECK PROCEDURES

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ABSTRACT

In complex human-machine systems, training, standardization, quality assurance, and actual operations depend on an elaborate set of procedures. These procedures indicate to the human operator the manner in which operational management intends to have various tasks performed. The objective is to provide guidance to the operators—in this case, pilots—to ensure a safe, logical, and efficient flight operations. However, all too often these procedures can become a hodge-podge, with little internal consistency and lack of a clear operational logic. Inconsistent or illogical procedures may lead to deviations from procedures by the flight crews, as well as difficulty in transition training for pilots moving from one aircraft to another.

This paper examines the issue of procedurization from two different, yet related, aspects: the overall design process of procedures and operational considerations. First, the authors describe a process that we call “The Four P’s”: philosophy, policies, procedures, and practices. We argue that an organization which commits to this process can create a set of procedures which are more internally consistent, which will be better respected by the flight crews, hence leading to greater conformity, and which will reduce the cost of transition training. Second, we discuss some of the operational considerations that must be taken into account while designing or evaluating flight-deck procedures. We focus our attention on extra-cockpit demands (e.g., scheduling of tasks based on demands from the environment) and intra-cockpit demands (e.g., procedure flow and cockpit layout).

The design process and operational considerations resulted from cockpit observations, extensive interviews with airline management and pilots, interviews and discussion at one major airframe manufacturer, and an examination of accident and incident reports involving deviation from standard operating procedures (SOPs). Although this paper is based on airline operations, it has been repeatedly demonstrated that these principles are also applicable to other complex human-machine systems, such as corporate aviation, nuclear power, chemical process control, military operations, and medical practice.

INTRODUCTION

A complex human-machine system is more than merely one or more human operators and a collection of hardware components. In order to operate a complex system successfully, the human-machine system must be supported by an organizational infrastructure of operating concepts, rules, guidelines, and documents. The coherence, in terms of consistency and logic, of such operating concepts is vital for the efficiency and safety aspect of this system.

In high-risk endeavors such as aircraft operations, it is essential that such support be flawless, as the price of deviations can be high. When operating rules are not adhered to, or the rules are inadequate for the task at hand, not only will the system's goals be thwarted, but there may be tragic human and material consequences. Even a cursory examination of accident and incident reports from any domain of operations will confirm this.

To ensure safe and predictable operations, support to the operators often comes in the form of standard operating procedures (SOPs). These provide the crew with step-by-step guidance for carrying out their operations. SOPs do indeed promote uniformity, but they do it at the risk of reducing the role of the human operators to a lower level. Furthermore, an exhaustive set of procedures does not absolutely ensure flawless system behavior: deviations from SOP have occurred even in highly procedurized organizations.

The system designers and operational management must occupy a middle ground—operations of high-risk systems cannot be left to the whim of the individual. But they likewise must recognize the danger of over-procedurization, which fails to exploit one of the most valuable assets in the system, the operator who is close to the actual operation. Furthermore, the alert system designer and operations manager recognize that there cannot be a procedure for everything, and the time will come when the operators of a complex system face a unique situation for which there is no procedure.

A dramatic example was provided by the Sioux City accident in which a United Airlines DC-10 suffered a total loss of hydraulic systems, and hence aircraft control, due to a disintegration of the center engine fan disk (National Transportation Safety Board, 1990a). When he had sized up the situation, the captain turned to the flight engineer and asked what the procedure was for controlling the aircraft. The reply is worth remembering: “There is none.” Human ingenuity and resource management were required: the crew used unorthodox methods to control the aircraft. This resulted in a crash landing, which well over half of the passengers and crew survived.

Procedural Deviation

Problems in using procedures usually manifest themselves in procedural deviation and resulting errors. If all goes well, these problems are not apparent to the operational management, and in most cases are left unresolved. They do become apparent, however, following a documented incident or an accident. Lautman and Gallimore (1988) conducted a study of jet-transport aircraft accident reports in order to “better understand

accident cause factors” in commercial airline operations. They analyzed 93 turbojet hull-loss accidents that occurred between 1977-1984.

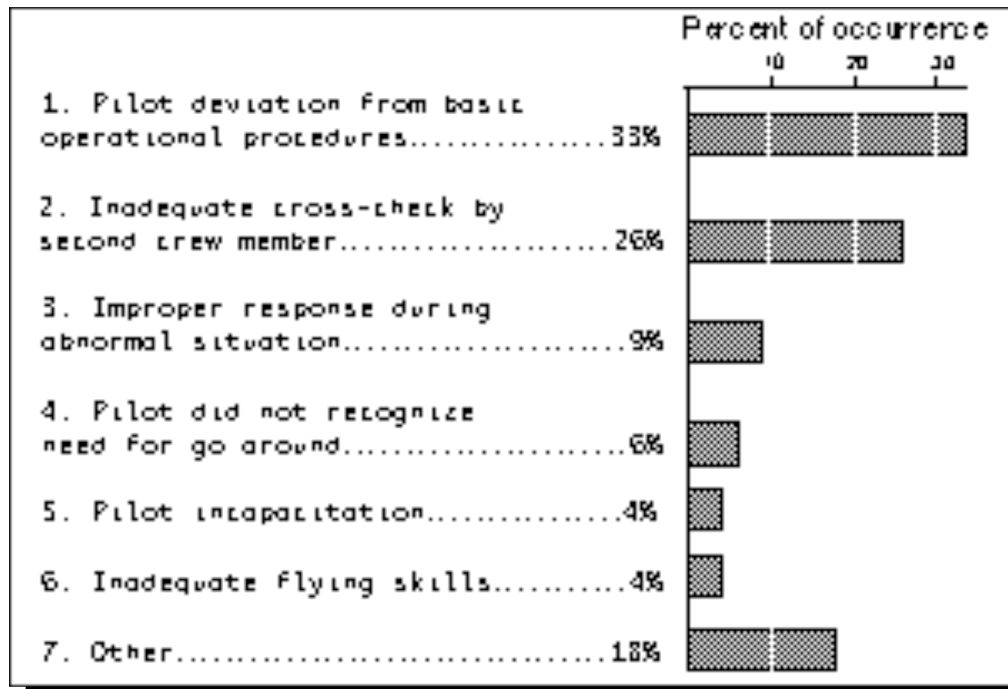


Figure 1. Significant crew-caused factors in 93 hull-loss accidents

The leading crew-caused factor in their sample was “pilot deviation from basic operational procedures” (Figure 1). Similar findings were highlighted in an airline safety study covering the years 1978-1990 (NTSB, 1994). Unfortunately, these historical findings were reinforced by the many procedure-related accidents that occurred in this decade (NTSB, 1990b; 1997).

We submit, however, that the classification of “pilot deviation from basic operational procedures” is misleading. A serious examination should go beyond the mere classification and attempt to unearth what were the factors that led a responsible flight crew member to deviate, intentionally or unintentionally, from a procedure. We should ask whether the procedures (from which the pilot deviated) were adequate for the task. What was the contribution of cockpit layout and design? Were the procedures compatible with the operating environment? How were they taught in ground school and how were they actually used on the line? Finally, were they part of a consistent and logical set of procedures, or just an assembly of instructions?

To answer these questions, we cannot look only at the aggregate level, i.e., procedures, but we also must examine the infrastructure, i.e., the policies and philosophy of operation—that is, the basis on which procedures are developed, taught, and used.

PHILOSOPHY, POLICY, AND PROCEDURES

Based on our field study with three major US airlines, we identified a link between the organization's philosophy, policies, and the standard operating procedures supplied to the pilots. We called this link the "Three P's" of cockpit operations. We shall now explore how an orderly and consistent path can be constructed from the company's philosophy of operation to the actual conduct of any given procedure (Degani and Wiener, 1994).

Figure 2 depicts this model. The fourth P, practices, will be introduced later.

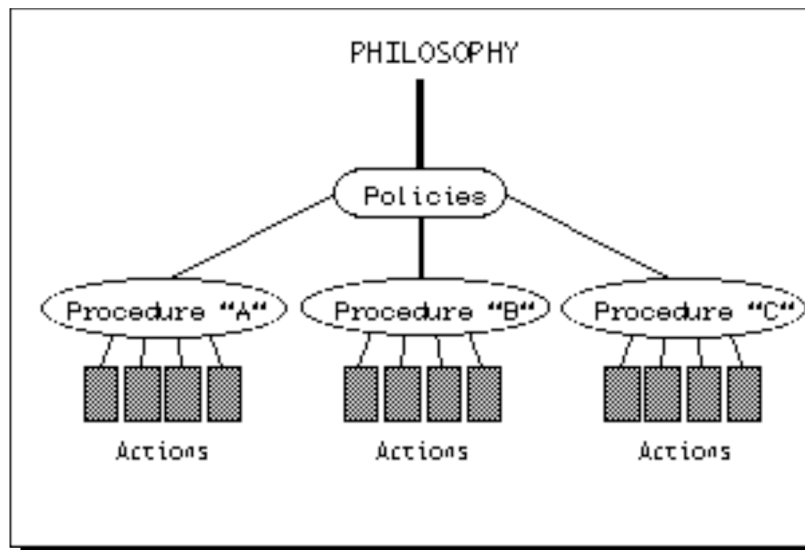


Figure 2. The "Three P's" model

PHILOSOPHY

The cornerstone of our approach to the design of cockpit procedures is philosophy. By philosophy we mean that the airline management determines an over-arching view of how they will conduct the business of the airline, including flight operations. A company's philosophy is largely influenced by the individual philosophies of the top decision makers, but also by the company's culture, a term that has come into favor in recent years in explaining broad-scale differences between corporations. The corporate culture permeates the company, and a philosophy of flight operations emerges. (For a discussion of cultural differences between carriers, see various chapters in Wiener, Kanki, and Helmreich, 1993).

Although most airline managers, when asked, cannot clearly state their philosophy, such philosophies of operation do indeed exist within airlines. They can be inferred from procedures, policies, training, punitive actions, etc. For example, one company that we surveyed had a flight operation philosophy of granting considerable discretion (they called it "wide latitude") to the individual pilot. Captains and first officers are schooled under the concept that they are both qualified and trained to perform all tasks. Consistent with this philosophy, the company until recently allowed the first officer to call for as well as conduct the rejected takeoff (RTO) maneuver (a maneuver that is only at the captain's discretion at most carriers).

The emergence of flight-deck automation as an operational problem has recently generated an interest in the philosophy of operations, partly due to lack of agreement about how and when automatic features are to be used, and who may make that decision (Wiener, 1989; Degani, Shafte, and Kirlik, 1999). This led one carrier, Delta Air Lines, to develop a one-page formal statement of automation philosophy (Figure 3). It is the first case that we are aware of where an airline management actually wrote out its philosophy and consequences of its philosophy on doing business (Wiener, Chidester, Kanki, Palmer, Curry, and Gregorich, 1991). In recent years other airlines followed suit and developed their own automation and procedure usage philosophies.

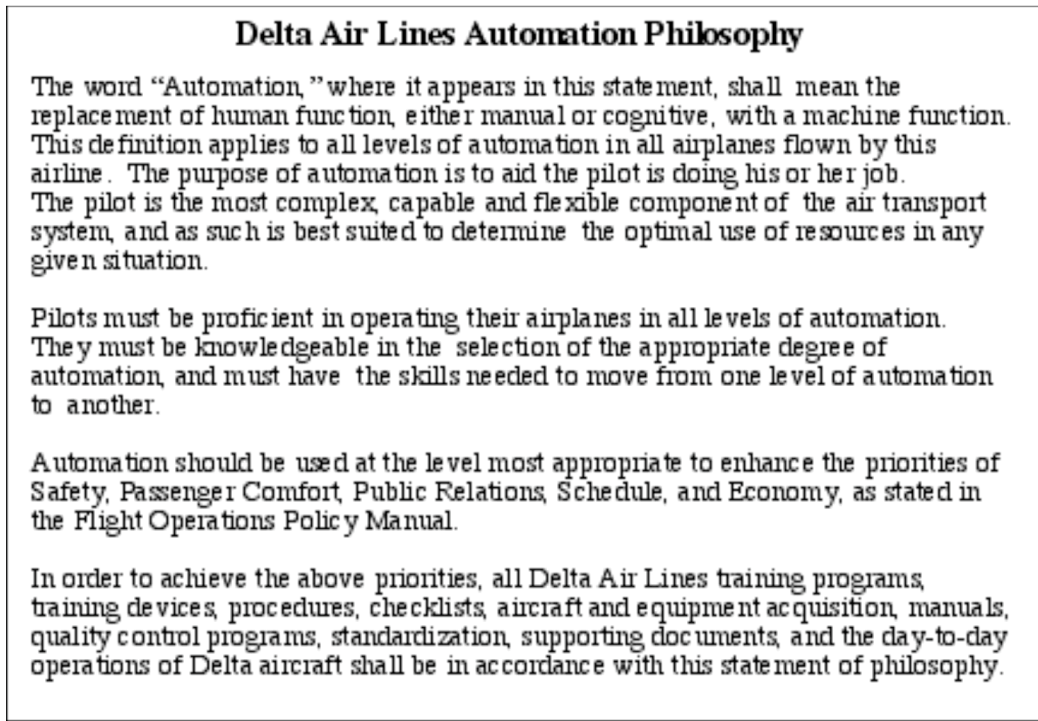


Figure 3. Delta Air Lines automation philosophy

Policies

The philosophy of operations, in combination with economic factors, public relations campaigns, new generations of aircraft, and major organizational changes, generates policies. Policies are broad specifications of the manner in which management expects operations to be performed (training, flying, maintenance, exercise of authority, personal conduct, etc.). Procedures, then, should be designed to be as consistent as possible with the policies (which are consistent with the philosophy).

The levels in the three-P framework are not rigid. For some elements of flight operations, there may be several policies; for others, there may be only a philosophy. For example, checklist SOP is a mature element of flight operation: there can be an overall checklist philosophy, as well as checklist policies for normal, abnormal, and emergency situations. Flight-deck automation is still an immature element; in this case there can be only a philosophy and procedures. As the operation becomes more mature, policies are defined and added. Philosophies may also change with time.

To illustrate the Three P's, let us assume that the task at hand is the configuration of an advanced technology aircraft for a Category-I ILS approach:

1. *Philosophy*: Automation is just another tool to help the pilot.
2. *Policy*: Use or non-use of automatic features (within reason) is at the discretion of the crew.
3. *Procedure*: On a Category-I approach, the flight crew will first decide what level of automation to use (hand-fly with flight director; autopilot and mode control panel; coupled; etc.), which determines what must be done to configure the cockpit.
4. Sub-tasks (or actions): Follow from procedures (e.g., tune and identify localizer and compass locator, set decision height, select autopilot mode, etc.)

Consider the following example of how policies that are actually remote from flight operations can affect procedures: One airline's new public relations policy called for more interaction between the cockpit crew and the passengers. It was recommended that at each destination the captain stand at the cockpit door and make farewells to the passengers as they departed the aircraft. This dictated a change in the procedure that most of the secure-aircraft checklist will be done by the first officer. Thus checklist procedures, which would normally be run by both pilots, yielded to public relations in order to be performed by a single pilot. The marketing department considered this particularly important, as they wanted the captain to be in place at the cockpit door in time to greet the disembarking first-class passengers.

To conclude, it is our position that procedures should not: (1) come solely from the equipment supplier, or (2) simply be written by the individual fleet manager responsible for the operation of the specific aircraft. They must be based on the operational concept of the organization, and on the organization's examination of its own philosophies and policies. When procedures are indeed developed in this manner, a logical and consistent set of cockpit SOPs are generated. It leads to a higher degree of conformity during both training and line flying and a marked reduction in the procedure-change cycles. Our ongoing experience has shown that this process and resulting set of procedures also enhance the general quality of flight operations and the morale in the pilot group.

THE FOURTH P: PRACTICES

The framework up to this point describes a process for procedure development. Yet it is incomplete. It overlooks the pilot for whom procedures are designed. To correct this, we have added an additional component—practices. The term “practices” encompasses what the pilot actually does. While a procedure may be mandatory, it is the pilot who will either conform to it or deviate from it. The deviation may be intentional or unintentional. Ideally, procedures and practices should be the same. The high prevalence of the “pilot deviations from SOP” classification in accidents and incidents indicates a possible breach in the link between procedures and practices.

The goal of flight management is to promote “good” practices by specifying coherent procedures. But we must also recognize that this is not always the case: a procedure may be poorly designed or inadequate for the situation at hand. The crew, however, has only two options: conform or deviate. A given deviation may be trivial (e.g., superimposing some non-standard language on a procedural callout), or it may be significant (e.g., not setting the auto-brakes according to the takeoff procedures). For example, we once observed a captain who, in response to the first officer’s question regarding the conduct of a mandatory procedure, replied “I just don’t do that procedure.” That captain unequivocally elected to deviate from the procedure. The immediate consequences of the failure to conform to a procedure can be seen in the following report submitted to the NASA’s Aviation Safety Reporting System (ASRS):

“Our flight departed late in the afternoon for San Francisco. During the flight we discussed the necessity to request lower altitudes from air traffic control (ATC), when approaching the San Francisco Airport, due to tendency to be “caught high” on arrival in this aircraft type. Area arrival progressed smoothly and we were cleared for the approach to the runway. When changing radio frequency from approach to tower (head down), the First Officer selected ‘open descent’ to 400 feet. The autopilot was off, both flight directors were engaged, and autothrottles were engaged. After contacting San Francisco tower, I became aware that we were below the glideslope, that airspeed was decaying, and that we were in an ‘open descent’ mode. I instructed the first officer to engage the ‘Vertical Speed’ mode in order to stop our descent, restore the speed mode for the autothrottles, and continue the approach visually. Company procedures explicitly prohibit selecting an altitude below 1500 feet for engaging the ‘Open Descent’ mode, since this places the aircraft close to the ground with engines at idle. It is suspected that this was the cause of a recent aircraft accident in Asia. ‘Highly automated’ aircraft demand explicit following of established procedures. Unfortunately, it is possible to fly the aircraft in numerous ways that will degrade your safety margin rapidly. Adherence to procedures would’ve prevented this incident.” (ASRS Report No. 149672)

To summarize, the ultimate factor that determines the quality of the system outcome is the actual practices. These may be governed by procedures, but they are not the procedures themselves. Management’s role does not end with the design of the procedure. Management must maintain an active involvement as the procedures move from the flight-management offices to the line and strive to reduce the differences between procedures and practices. This is generally approached as a “standardization,” a form of quality assurance aimed at ensuring compliance.

OPERATIONAL CONSIDERATIONS

Philosophies, policies, and procedures must be developed and designed with full consideration of the operational environment in which they will be employed. Commercial aviation procedures are complex because of the ever-changing environment (e.g., weather, scheduling demands, airport limitations). In order to successfully manage the flight, cockpit procedures must be compatible with the equipment itself (e.g., menu structure of flight management computer) as well as with external demands (e.g., air traffic control). The following discussion will present the procedure design

considerations associated with extra- and intra-cockpit tasks. For a detailed discussion, see Degani and Wiener (1990; 1994).

Extra-Cockpit Activities

Many cockpit procedures are dependent on the activities of exterior agents such as air traffic controllers, dispatchers, maintenance crews, gate agents, and cabin crew. The design of such procedures must be compatible with (1) the structure of these external demands and (2) the methods that can be used by the cockpit crew to respond. For example, one company's SOP requires a check of log books for open maintenance items prior to activating any controls or switches in the aircraft. The logic behind the procedure is that this check will prevent a flight crew member from activating a system that may be inoperative, thereby causing more damage (e.g., attempting to start an inoperative power unit). At most stations, the aircraft log books are in the cockpit when the flight crews come on board. However, at some remote stations, due to special maintenance procedures, the log book is brought to the aircraft five minutes before push-back. Therefore the procedure cannot be accomplished in those stations. A change in the procedure, so that this information can be obtained from another source, or a change in maintenance procedure is required to defeat this incompatibility.

This is an example of what we call "system procedures." The system in this case involves not only the cockpit crew and the aircraft, but also agents and activities external to the cockpit. Such system procedures must be developed by using a common definition of the task and involving all the components of the system in the design of the procedures and policies. If such system procedures are designed piecemeal, then the product may be an inefficient procedure, unbalanced set of responsibilities, and complicated dependencies. All are foundations of a potential system breakdown.

Scheduling of procedures

Two factors affect the flow of procedures in the cockpit: first, the sequencing of tasks and procedures, which is specified by the designer of the SOPs; and second, the actual scheduling of tasks and procedures, which is conducted by the cockpit crew. The goal is to optimize the sequencing in the design process and to promote efficient scheduling by the crews. The designer's goal is not merely to reduce workload, but also to distribute it throughout the phases of flight in order to avoid periods of very high or very low workload. While this is important for any routine operation, it appears to be extremely important in today's automated two-person cockpit (Wiener, 1993).

Window of opportunity

For every task on the flight deck, there is a "window of opportunity" defined by physical boundaries. For example, the window of opportunity for conducting the "DESCENT" checklist can be defined as the segment between cruise altitude and 10,000 feet. This segment can be translated into a time period during which the procedure must be executed. This time period is not a constant, but varies as a function of the cruise altitude, rate of descent, and atmospheric conditions. Although a given task can be effectively accomplished anytime within this segment or window, it appears that there is an advantage in conducting the task early in the window of opportunity (Laudeman and Palmer, 1995; Raby and Wickens, 1994)

The above discussion is applicable to a recent airline accident in which a MarkAir Boeing B-737 crashed short of the runway at Unalakleet, Alaska. The captain, who was flying the aircraft, misread his chart and started descending five miles earlier than he should have (as indicated on his aeronautical chart). Consequently, the aircraft struck the terrain several miles short of the runway. The National Transportation Safety Board (NTSB) stated in its accident report that the first officer (copilot) did not notice or did not inform the captain of his error (1991). The NTSB believed that this is because the first officer was preoccupied with other cockpit duties. The first officer had two tasks to perform: (1) reconfiguring the engine bleeds to prevent foreign object damage; and (2) starting the auxiliary power unit. The Safety Board found that the copilot was overloaded with configuration tasks that could have been done earlier, and therefore could not keep up with monitoring the progress of the approach and backing up the captain's actions. The window of opportunity for reconfiguring the bleeds began during the descent phase and should have ended long before the final-approach phase. The NTSB recommended that MarkAir change its checklist and procedures accordingly.

Decoupling of tasks

Tight coupling is a mechanical term which is used here to denote a phase, or a task, made up of several actions that are interrelated, performed simultaneously, and are time dependent (Perrow, 1984; 1986). The problem with tight coupling is that when unexpected events occur, the time dependency and the interrelation between components make it difficult for operators to intervene quickly and efficiently in order to contain the unexpected situation. A takeoff is an example of a tightly coupled task because of the time dependency and the relation to other aircraft on the ground and in the air.

We use the term decoupling to denote the process in which the designer is trying to “break away” some of the interactions inherent in a phase or a task. In decoupling an activity, criticality is an important factor. Not all cockpit tasks conducted during the same phase of flight are equivalent in terms of criticality. Some may be more critical (e.g., monitoring the final approach), some may be less (e.g., making cabin announcements). In most cases, the primary tasks are continuous (taxiing the aircraft, tracking a glide slope, etc.), while the secondary tasks are discrete tasks (entry of manifest changes into the computer, configuring bleeds, running checklists). Critical primary objectives should be well “guarded.” This can be done by decoupling secondary or tertiary tasks that may interfere with performing the primary task.

Intra-Cockpit Activities

Procedures are an integral part of the pilot-machine interface. Procedures, therefore, must be compatible with the machine. For example, the procedure that dictates the sequence of items in programming a flight-management-computer must be compatible with the structure of this interface in terms of hierarchy, page layout, and the text to be entered; otherwise, data-entry errors will take place.

Flow of procedural steps

In the cockpit of an airplane, the instruments, units and system panels are arranged in a certain “geographical” locations according to frequency of use, criticality, and other human-factors considerations. In designing efficient and error resistant procedures, the

steps must follow some logical and efficient flow of motor and eye movement along the cockpit panels. Checklist procedures that serve to verify the accomplishment of these setup procedures can also be conducted in the same sequence. For example, one can conduct the “BEFORE ENGINE START” checklist from the aft (upper) portion of the overhead panel, moving with the checks toward the lower part of this panel. By using a top-to-bottom order of checking panels and items, the design can accommodate a population-stereotype for sequencing of actions and biomechanical considerations (Degani and Wiener, 1990).

Aircraft systems and procedures

A procedure that details how to operate a particular sub-system must be accurate and compatible in terms of its procedural steps, actions, and flow. The following examples show how much the procedural designer must be attuned to the engineering aspect of the equipment. One company’s emergency procedure for coping with asymmetrical-flap-extension (which can have a significant effect on lateral control of the aircraft) had to be rewritten when it was found to be inaccurate. The problem? The power supply for activating the flaps, following asymmetrical flap extension, was different from the standard configuration for this model aircraft. The airline, which originally specified the non-standard power supply configuration, failed to modify the procedure accordingly. (The inaccurate procedure was in effect for some five years before it was detected).

Cockpit layout and procedures

During our studies we observed instances of incompatibility of procedures with the ergonomic layout of the flight deck. Consider the flap/slat and gear levers, for example. Traditionally, gear and flap/slat levers were mounted in the first officer’s area (right side of the cockpit). They are not within easy reach for the captain in the cockpit of a wide-body airplane. In most U.S. airlines the captain and the first officer rotate the duties of pilot-flying and pilot-not-flying each flight. If the first officer is the pilot-flying, the SOP usually dictates that the captain raises the gear and flaps/slats after takeoff. To do this, the captain must lean to the right of the throttle quadrant to grasp the gear or flap/slat lever(s). In several wide-body aircraft cockpits, the captain cannot see the flap/slat detents well and he or she can accidentally push the throttles rearward (an action that will lead to thrust reduction during climb). Similar problems in reaching for a lever may occur when the first officer, as the pilot-flying, manipulates the speed-brakes which are located close to the captain seat and across the throttle quadrant.

There are two approaches for solving this incompatibility: (1) procedural change, and (2) hardware change. Some have argued that since the existing cockpit layout cannot be changed (within reasonable boundaries of cost efficiency), the procedure should be changed so that when the first officer is the pilot-flying, he or she will retract/extend the gear. In contrast, the designers of new generation aircraft such as the Airbus A-320 and McDonnell Douglas MD-11, located these levers on a pedestal between the two pilots. It is within equal reach distance for both the captain and the first officer. Indeed, these aircraft were designed during a different social era than their predecessors. Social culture has affected the airlines’ philosophies of operation (a flatter cross-cockpit authority gradient) and the airlines’ policies (rotation of pilot-flying duties), and has thereby

affected associated procedures. To fit the new philosophy, policy, and procedures, the cockpits were designed accordingly.

Paperwork and procedures

Documents, manuals, checklists, and many other paper forms are used in the cockpit. The compatibility between the procedures and their associated devices (manuals, checklist cards, etc.) affects procedural execution. Ruffell Smith (1979) reported that excluding aircraft flight manuals, the amount of paperwork required for a flight from Washington D.C. via New York to London, had a single side area of 200 square feet. Interestingly, the 15 years since Ruffell Smith's study have not yielded any reduction in cockpit paperwork. On the contrary, the problem has only intensified (Degani, 1992). During one cockpit observation we encountered a situation that exemplifies this problem:

While the aircraft was taking off, the "Hydraulic RAT Failure" warning appeared on the aircraft's electronic monitoring display. The concern was whether the ram air turbine (RAT) was unlocked and hanging down from the belly of the aircraft. The captain aborted the takeoff, and then taxied to an adjacent taxiway in order to conduct the appropriate procedure. However, he could not find the procedure that specified how to verify whether this indication was true or false (RAT sensor failures have occurred in the past). There were five places where this procedure could reside: (1) the Flight Operational Manual, (2) the Supplemental section in the flight manual, (3) Operations Bulletin, (4) the aircraft newsletter, and (5) on the dispatch paperwork. The procedure could not be found in any of these. An attempt to find it using an index failed—there was no index in the manual. The captain called the local maintenance station and asked them to read it to him on the radio. They could not find it either. After waiting for several minutes, he decided to conduct the procedure from memory—a clear violation of a company policy that requires that procedures must be conducted from the book and not by memory. (These deficiencies have since been corrected by the airline.)

We argue that the entire documentation supplied to the cockpit (and elsewhere) should be regarded as a system and not as a collection of independent documents. With the advent of laptop computers and powerful graphics and communications capabilities, new "electronic flight bag" devices are entering the cockpit (Avionitek, 1998). They provide an opportunity to rethink the way information is provided to flight crews and may dramatically change the way procedures are conducted on the flight deck.

CONCLUSIONS

Flight deck procedures are the backbone of cockpit operations. They are the structure by which pilots operate aircraft and interact with other agents in the system. Procedures are one of the most important factors in maintaining flight safety—during both normal and abnormal conditions. It was traditionally believed that procedures are only equipment dependent—that they are inherent in the machine's function. We have tried to show throughout this paper that this is not the case. We argue that they are also dependent on the nature of the company's operations and the operational environment in which the crew operates. Convergence of these aspects must take place for a coherent and efficient procedure to emerge.

There is no “royal road” to procedure development. There is no such thing as an optimal set of procedures. No manager will ever be able to “open up the box,” install the equipment, and install “good” procedures along with it. Nor do we anticipate that any computer technology can make this easier. Pilots are trained to fly by procedures. Aircraft are built to operate by procedures. Government regulations are based on procedures. It is a long, tedious, costly, exhausting process. We do not know of any shortcuts.

ACKNOWLEDGMENTS

This paper is based on several NASA research projects conducted by the authors. We gratefully acknowledge the cooperation of Continental Airlines, Delta Air Lines, Northwest Airlines, the Air Line Pilots Association, Boeing Commercial Airplane Company, and America West Airlines. The opinions expressed in this paper are those of the authors and not of any institution or organization.

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